In this memoir Hann throws out a new thought toward the explanation of the constant semidiurnal wave of atmospheric pressure. He asks whether possibly the absorption of the radiant heat from the sun by the upper strata of the air can be the source of this wave and of its constancy.

It is easy to perceive that by the periodic diurnal influence of the solar rays on the upper layers of the atmosphere occurring similarly day after day, periodic motions of great regularity must arise in the upper strata of the atmosphere, viz, an oscillation of the whole mass of the atmosphere. These motions can explain the typical character of the diurnal oscillations of the barometer, whereas the local differences represent the basis of the element that modifies the result.

We here see that Hann had correctly appreciated the *amplitude* of the double wave of pressure.

In this elegant little memoir it is interesting to perceive the demonstration that the magnitude of the amplitude of this wave has nothing to do with sun-spots, whence Hann correctly draws the following conclusion:

This diurnal oscillation of the pressure can not depend on the electricity of the sun, as was thought by Lamont, for in that case it must certainly have a period in common with the magnetic variations which evidently depend upon the sun-spot period.

(25) **Angot.** Étude sur la marche diurne du baromètre. [See (11).] On page B311 he says:

An examination of the figures in Table 4 shows that the semidiurnal wave is a complex wave resulting from the interference of two distinct waves. One of these, which we shall call the *secondary semidiurnal wave*, presents one maximum and one minimum in the course of the year like the diurnal wave and, like it also, is influenced by local conditions. * * * This secondary wave is then certainly due, like the diurnal wave, to the diurnal variation of the temperature of the lower layers of the atmosphere. The second wave, which we shall call *the principal semidiurnal wave*, presents very different characteristics; its amplitude experiences a double variation in the course of the year; it is a maximum at the two equinoxes, and a minimum at the solstices. * * * One can indeed already foresee that the phase of this second wave for one and the same station is constant throughout the year.

Again on page 338 Angot says:

The diurnal curve of the barometer can be considered as the resultant of the superposition of two waves having very different origins and characters. One of these waves is independent of the special geographic conditions of each station; it depends only on the position of the sun in its orbit and on the latitude.

After Angot has remarked that perhaps it may be possible that this "semidiurnal, principal wave" also has a term containing the 4-fold angle ($\psi+4x$), but in that case its amplitude certainly can not be even 0.02 to 0.03 mm., he then proceeds to say:

The second wave can be represented by a series such as

$$a_1\cos(x+\psi_1)+a_2\cos(2x+\psi_2)+a_3\cos(3x+\psi_3)\ \ldots$$

This wave is caused, at least in great part, by the diurnal variation of temperature in the lower layers of air, and consequently all its coefficients depend not only on the latitude and the season but equally on the particular situation of each station; the coefficients change their values with every change of condition and every local influence that can modify the diurnal variations of temperature; we are therefore justified in calling this second wave by the name "thermal wave."

(26) **Margules.** Ueber die Schwingungen periodisch erwärmter Luft. Situngsb., K. Akad. d. Wiss., math.-naturw. Kl., Wien, 1890, **99**: 204–227.

Translated in—

Abbe, C. Mechanics of the earth's atmosphere. Washington, 1891. (Smithsonian misc. coll. No. 843.) pp. 296–318.

(27) **Thomson, Sir W.** On the thermodynamic acceleration of the earth's rotation. Proc. Royal soc., Edinburgh, 1882, **11**: 400. *See* Margules (26), page 207.

III. *Wind.*

(28) **Pernter.** Die Windverhältnisse auf dem Sonnblick und einigen anderen Gipfelstationen. Denkschr., Kais. Akad. d. Wiss., Wien, **58**: 209, ffg.

(29) **Pernter.** Idem, pages 206 and 207.

(30) **Helmholtz.** Ueber atmosphärische Bewegungen. Sitzungsb., Kgl. preuss. Akad. d. Wiss., Berlin, 1888. *Reproduced in* Meteorologische Zeitschrift, 1888, **23**: 329.

Translated in—

Abbe. Mechanics of the earth's atmosphere. Washington, 1891. (Smithsonian misc. coll., No. 843.) pp. 78–93.

(31) **Köppen,** in his remarks on Hann's great work:

"Die tägliche Periode der Geschwindigkeit und Richtung des Windes." Sitzungsb., d. Kais. Ak. d. Wiss., 2 Abth. Wien, **89**: 11 ffg.; *also in* Meteorologischen Zeitschrift, **14**: 343; and more extensively in Annalen d. Hydrographie, **11**: 625.

(32) **Sprung.** Lehrbuch der Meteorologie, page 341.

(33) Almost every trace of variation in the diurnal curve is lacking on the ocean.

(34) **Sprung.** Deutsche Meteorologische Zeitschrift, **1**: 15.

(35) The many additional items added by Sprung by counting the rotation of the windvane, are based in general on observations made only three times a day, and this insufficient observational material may certainly explain the result attained by him.

ON THUNDER.[1]

By Wilhelm Schmidt.

[Dated K.k. Zentralanstalt für Meteorologie u. Geodynamik, Vienna, 1914.]

1. From earliest times a thunderstorm, and particularly the thunder and lightning, has made the greatest impression on man. It is, therefore, all the more strange, that precisely these phenomena have remained so little studied, and that our knowledge of the sound phenomena has not been increased by more experiments that are something more than analogies. And yet it is not at all difficult to secure results in this field. Observations that may be made when it thunders, themselves point the way to such experiments. Beside the extremely violent, usually deep-toned peals—though they sometimes have a clear ringing or a rushing sound—one may also hear the ringing or breaking as of window panes accompanying some heavy thunder crash; the vibrations can even be perceived by the sense of touch, and sometimes by the trembling of the ground. Thus phenomena whose intensity far exceeds that producible by sound, demonstrate that other vibrations than the audible ones are also present. The very depth of the tone leads to the assumption that there are yet deeper toned pressure variations of such few vibrations that they are inaudible and the direct cause of the effects mentioned. We shall, therefore, endeavor to demonstrate these vibrations which are something quite novel in nature, as well as to complete the picture by recording the audible vibrations.

METHODS FOR RECORDING THE VIBRATIONS.

2. *Instrument I.*—Two different instruments, I and II, serve to accomplish these two purposes. The instrument, I, designed to record the longer vibrations could use a mechanical registration since there was considerable energy available and the velocities to be recorded were not too great. In its final form, I consisted of a wooden box of 210 liters capacity, having all its joints carefully sealed, and with a hexagonal aperture of more than 250 sq. cm. in one of its sides. This aperture was almost closed by a very light aluminum plate suspended by means of two long threads, so that the plate could swing freely in and out. Thus every atmospheric compression-wave falling upon the box must also compress and reduce the volume of the air within the chamber and the aluminum plate, acting as a piston, swing inwards. The reverse process was caused by a rarefaction of the air. A simple train of levers was sufficient to transmit these vibrations to a recording pen writing on the moving sheet of a chronograph. Experience with seismographs shows that the best device is the endless strip of smoked paper running over a motor-driven cylinder upon which rests the recording point of the pen arm. The band of record paper is stretched by a free roller suspended in the lower loop and set at a slight angle with the driven cylinder thus causing a lateral shifting of the record strip and a spiral record. With a slight friction it was possible to secure recording speeds of 5 to 8 mm. per second. The record was fixed by means of a shellac solution in the usual way.

3. *Standardization of instrument I.*—It would be a mistake to assume that the displacement of the pen is proportional to the variations in pressure. The inertia

[1] Author's abstract (German) of the two following papers: "Analyse des Donners," Sitzungsb., K. k. Akad. d. Wissens. IIa, Wien, 1912, 121: 2045.
"Ueber das Wesen des Donners," ibid., IIa, 1914, 123.
Translated from Meteorologische Zeitschrift, Braunschweig, Okt. 1914, 31: 487–498.—C. A. jr.

due to the mass of the aluminum plate and of the air itself, the period of vibration of the whole system, the partial equalization of pressure within and without the chamber by means of the open interval around the plate, and finally friction, all these induce a delay and particularly a change in the magnitude of the pen displacement which can, of course, be computed from the measurements but are much better determined empirically. For this purpose a hole is bored in the wall of the chamber and a closed glass tube, fitting it quite closely, is inserted and pushed in or withdrawn by hand. If the stroke of this glass piston is regulated by means of collars fitted to it, and if one limits himself somewhat to producing the gentler waves, then the changes in volume produced by the piston stroke may be converted into pressure changes which may be compared with the curves simultaneously recorded by the instrument. There is here the advantage of being able to pick out only those waves of regular form and having the period of vibration simultaneously recorded. Indeed the latter primarily determines the magnification. For example, a pressure wave whose amplitude [corresponds to a pressure change] of 1 mm. mercury shows—

Time of vibration.	Deflection of recording pen.
Seconds.	*Mm.*
0.2	41
.4	79
.6	53
.8	29
1.0	20
3.1	5

Whence it appears that very rapid and very slow vibrations are least pronounced; the period of vibration of the system and consequently the strongest magnification lies in the neighborhood of 0.4 second. The conversion of the recorded vibrations is carried out by the aid of the above values. This method of standardization brings the special advantage that the numbers do not hold true in the case of the deflections produced by an infinitely long series of similar waves but, by reason of the involuntary variations in the wave lengths produced during the standardization, hold only for isolated deflections such as are significant in thunder.

4. *Instrument II.*—The second instrument, II, designed to study the sound vibrations of thunder, employs a method somewhat approaching the smoke-ring method used by Marbe (1). A graphophone horn of 57 centimeters aperture stands at right angles to the window, with its mouthpiece (reproducer end) applied laterally to a short upright chimney of less than 4 square centimeters cross section. All compression waves (Dichtewellen) that strike the large end of the horn are propagated with much magnified amplitude into the chimney and induce vibrations in a small smoky turpentine flame. The upper end of the flame, extending beyond the top of the chimney, was intercepted at about 5 mm. from the chimney top by a moving strip of telegraph paper driven at the rate of about 145 mm. per second by an electric motor. Appropriate screens caused the smoky flame to deposit a uniform band of soot when the flame was at rest; but every jump of the flame, every condensation or rarefaction of the air, caused a heavier or lighter deposit of soot so that transverse bands were deposited upon the paper strip. The measured interval between two such bands and the known speed of the paper permits the determination of the time interval between two individual successive condensations. The rough surface of the paper used held the soot so firmly that one could "fix" the important portions of the record at a later time.

The advantages of this device are: the absence of coarse inert masses, a minimum frictional effect, the possibility of expanding the time scale with a consequent more detailed analysis of the processes studied, and finally the small cost which removes any limits to the length of the record strip used (e. g., 700 meters for a thunderstorm). The only appreciable disadvantage lies in the fact that while instrument II permits qualitative observations such as the duration of vibrations, it is possible to make only rough quantitative gradations according to the intensity of the coating.

5. *Installation; Time determination.*—For a time both devices were set up and in running order in the laboratory of the K. k. Zentralanstalt für Meteorologie u. Geodynamik in Vienna. On the approach of a thunderstorm it was merely necessary to open a window, switch in the motor, and light the turpentine lamp. An important matter here, however, was the time-recording device for it was only by its aid that one could correlate the simultaneous records of the two instruments, and the contemporaneous notes on the character of the audible sound phenomena, the distance of the lightning, etc.

To secure the time record the anchor escapement, or lever, of a simple alarm clock was so modified that a single oscillation of the lever closed and opened an electric circuit, thereby making time marks alongside both the curve of instrument I and the soot band of No. II. An additional key inserted in this time circuit permits the time marks to be interrupted at any instant, thus furnishing a ready means of distinguishing them. The latter procedure was used on instrument II only when it was desired to test the speed of the paper band; otherwise the slightly confusing succession of time marks on this record was replaced by consecutively numbered little pasters stuck on the strip promptly after each thunderpeal, thereby giving ready identification of the corresponding portions of the record.

Records with instrument I were secured during the summer of 1912, and both instruments simultaneously recorded some thunderstorms during the summer of 1913. In the following pages are first discussed the results of studies of sound vibrations due to thunder, which are in part known to the ear; afterwards I consider the more violent pressure variations of somewhat longer duration which present something fundamentally new.

RESULTS OF THE RECORDS.

Sound waves.

6. *General review.*—Instrument II, in its final form, began its records with the two thunderstorms of August 6 and 12, 1913, and approximately 20 audible thunder peals. In each case the effect of the air vibrations was recorded as a pronounced rapid alternation of light and dark bands across the record paper in place of the otherwise uniform gray soot coating. The time of duration of each could be simply determined from the interval between two adjacent bands. The general appearance of the record showed that the most diverse kinds of vibra-

tions succeed one another in a thunderpeal; beginning with about 25 per second (a lower number was not so readily perceived) and ranging up to more than 100. These vibrations formed an uninterrupted series, but pronounced regularity was not to be remarked except in the later portion of the thunder; most cases showed a merry mixture of series of shorter and longer vibrations, particularly immediately after the first impact and later at the occasional pronounced intensifications. It thus appears that only individual portions of the thunder can be regarded as a "tone." The other portions are at the best but "noises," if this name is applied to the irregularity of the time intervals alone and not made to include the usually wholly arbitrary implication that one here has primarily to do with specially rapid vibrations.

Now generally irregular pressure fluctuations must change and weaken much more rapidly during their propagation than do regular fluctuations, and this is intensified as the interval shortens. If these records of thunder that has already traveled a considerable distance (in all cases I observed a marked interval between the lightning and the first sound) enable us to infer the procedures in the vicinity of the lightning path, then we here have to do with a series of very violent, irregular, pressure fluctuations taking place in particularly rapid succession; there the (klirrende, knatternde) rattling, clanking thunder has a much higher, almost metallic Klangfarbe (tone color). The appropriateness of the term "clanking" (klirrende) is shown by the experiment where the closed window was smartly struck; the apparatus then recorded vibrations that were in general quite similar to those of thunder.

The fine variations in the shades of the smoked record of instrument II unfortunately are not adapted to clear reproduction. They were therefore translated into numbers with the aid of a numbered scale of shades of black and grays, the highest numbers (plotted as ordinates) indicating the deepest blackening or the most violent pressure waves. In this way has been constructed figure 1 [omitted], which shows the translated record obtained on August 6, 1913, during the first seconds of the thunder at 2:44 p. m. In this very carefully executed twofold copying the regularities were involuntarily emphasized; however, it is clearly shown that immediately after the first somewhat slower vibrations, very rapid changes set in at once and that the same procedure takes place after the first node of the thunder.

7. *Statistical summary.*—Of course such a detailed treatment was not possible for all the cases of thunder. In its place I attempted to characterize the variations by a statistical method, by determining the duration of each thunder and then to compute the frequency of occurrence of the peals of various durations. In this way was obtained column 2 of Table 1, from the three most completely recorded thunders, the numbers of waves being grouped by equally spaced intervals of the number of vibrations per second. But one is not to assume that in speaking of the "number of vibrations per second" we ever measured a long, regular series of them. Even two successive vibrations seldom had exactly the same duration. The concept "tone" is here in mind, since this name is at times also applied to single waves.

TABLE 1.—*Distribution of frequency of rapid vibrations in thunder.*

Number of vibrations per second.	Number of waves.	Rough distribution of energy (ratios).
15–25	70	569.6
25–35	52	180.1
35–45	40	76.9
45–55	24	29.5
55–65	22	17.8
65–75	18	10.9
75–85	42	19.6
85–95	56	20.5
95–105	62	18.6
105–115	71	17.7
115–125	45	9.5
125–135	25	4.5
135–145	23	3.6
145–155	16	2.1
155–165	14	1.6
165–175	12	1.3
175–185	9	0.8
185–195	6	0.5
195–205	5	0.3

According to this table the most likely tones to hear in thunder are those with 15 to 40 vibrations per second (E, the second E below the bass clef); those of 40 to 75 are less frequent, while higher tones, 75 (D# in the bass) to 120 or A are again of frequent occurrence. Tones of yet higher vibrations, such as those usually met with in music, are again quite rare.

As only those vibrations were measured that exceeded a definite intensity, the above figures do present the distribution of intensities to a certain degree; nevertheless they are not to be regarded as an expression of the distribution of energy. Values are indeed given, and for these a wave of longer duration had the same value as one of shorter duration. If it is desired to pass to energies then the intensities are to be multiplied by the times of their duration, i. e., by the reciprocals of the vibration numbers (given in column 1); thus are secured the values in column 3 of Table 1, where the generally uniform character of the distribution gives particular emphasis to the extraordinary prominence of the longest waves with vibration numbers below the limit of sound. The manner of recording is less favorable to the registering of yet longer vibrations, and as a matter of fact the contrast is really much greater than our table can express.

Pressure vibrations of longer duration.

8. *General review.*—The whole distribution of the energy permits one to anticipate that yet slower vibrations play a large part. For various reasons these slower vibrations could not be adequately recorded by means of instrument II; but it was otherwise with instrument I, which was designed to reveal precisely this class, and which furthermore permitted quantitative determinations. As early as the summer of 1912 records of this kind had been secured, but the much more reliable standardization was not carried out until 1913, and we shall therefore restrict this discussion to the four thunderstorms at the end of July and beginning of August of that year, embracing 47 thunderpeals. Ten of the peals were vigorous enough to yield well developed records throughout.

In general the strongest pressure variations uniformly showed relatively long periods lying between 0.2 and 0.5 second with a maximum of 0.54 second. Even when they were far below they coincided with the limits of audibility,[2] points of the greatest audible loudness, the "beats" and "nodes" of the thunder indeed briefly preceded them; so that in every case the first vibrations to arrive were slow ones even though slightly later accompanied and followed by more rapid ones.

9. *Precise evaluation—Energy content.*—In the case of those 8 thunderpeals where the pen did not jump over the paper too fast (this was not altogether avoidable), the records were evaluated by measuring and computing the duration and amplitude of the strongest waves. In the case of the thunder of August 6, 2:46 p. m., all the plainly distinguishable variations were thus measured. The results of this last-mentioned case are presented in Table 2. The greatest durations of vibrations are fairly uniform according to their magnitudes; as mentioned above, they range between 0.20 and 0.54 second, and if the change were repeated regularly might be regarded as tones lying one or two octaves below the limit of audibility. On the other hand the maximum variations in pressure measured between the extreme positions are far more contrasted. The highest value of the pressure is 0.017 mm. of mercury, which is very considerably above that of the strongest sound.

TABLE 2.—*Determinations of 17 of the stronger waves of the thunder at Vienna on Aug. 6, 1913, at 2:46 p. m.*

Duration of vibration.	Amount of vibration.	Intensity of wave.	Energy of wave (internal).
Secs.	*Mm.* of Hg.	*Erg/cm.² sec.*	*Erg/cm.²*
0.32	0.017	1.63	0.522
.24	.005	0.11	.026
.38	.004	.09	.034
.16	.003	.06	.009
.18	.006	.18	.032
.20	.004	.08	.015
0.22	0.002	0.01	0.003
.22	.004	.11	.024
.18	.013	.92	.166
.34	.014	1.02	.347
.16	.003	0.06	.009
0.24	0.003	0.05	0.013
.38	.002	.01	.005
.24	.003	.05	.013
.22	.004	.09	.019
.14	.004	.08	.011
.28	.003	.04	.025

One can now calculate by means of the pressure changes, the intensity, I, of the sound, i. e. the amount of energy passing in 1 second through 1 square centimeter of a plane perpendicular to the direction of propagation of the sound. In the formula (1)

$$I = \frac{\rho c^3}{2\kappa^2}\delta'^2$$
$$= 0.304 \times 10^{10}\delta^2$$

the velocity of sound, c, at 18°C. and the mean pressure 743 mm., was taken as 342.8 meters per second and the specific gravity, ρ, as 0.001186. The ratio of the specific heat of air, κ, is put at 1.402; the pressure amplitude δ' in the first expression is in absolute measure, δ in the second expression is measured in millimeters of mercury. Thus are derived for this one thunder, the figures given in column 3 of Table 2, and multiplying these by the duration in time of each individual vibration they are converted into the energy-amounts given in the last column. It is now possible to compute the total energy embodied in the pressure variations of this thunder peal. By adding the values in column 4 there results 1.27 erg/cm² for the evaluated vibrations which occupied a time interval of 4.1 seconds. Now if it is assumed that the total duration of the thunder was 13 seconds, which is probably close to the actual facts, and that the mean intensity during the missing 8.9 seconds which was too small to measure, was approximately 0.01 erg/cm²sec., then the total energy amounts to about 1.4 erg/cm.[3] Further, suppose that the origin of the disturbance had the form of a point and was 5 km. (which is too far) distant from the point of observation then, disregarding losses due to friction and other causes, the *total energy* of the thunder amounted to 22,000 meter-kilograms (2).

[2] In extreme cases the limit of audibility is about 0.05 second duration of vibration, yet in such cases the hearing is regarded as very sensitive.

10. *Comparison with the energy of lightning. Energy loss.*—For comparison we may deduce the approximate value of the energy of lightning. Riecke gives 95 coulombs as the quantity of electricity transported in the stronger discharges; the tension is probably overestimated at 10^9 volts; whence the energy is approximately 10^{10} meter-kilograms, a value quite disproportionately in excess of that of the computed energy of thunder.

Although the necessity of making arbitrary assumptions in the calculations greatly impairs the reliability of both values, neverthleess it is quite certain that their magnitudes are widely different; hence it is certain that at a short distance away only the smallest fraction of the energy of lightning is still present in the form of pressure vibrations.

There are two plausible causes for this perhaps somewhat unexpected result: (1) A considerable amount of energy is consumed in the nonmechanical forms of heat and light at the time of the discharge; (2) the propagation of such pressure vibrations, both much greater than those of ordinary sound and also of irregular character, causes a considerable loss in intensity. But this second cause must also find expression in the fact that the individual thunder peals, which generally originate at different widely separated lightning bolts, show corresponding mutual departures. These facts are revealed much better by the original records than by the evaluated curves and tables. Figure 2 [omitted] shows approximately the first four seconds at the beginnings of three thunder records. Only one of them starts off at once with one of the most pronounced pressure vibrations, in one case the vibrations increase more gradually to the maximum. But one may distinguish similar differences in the thunder sounds that come to our ears: Some begin at once with a heavy crash after which the intensity decreases (we need not here consider the cases of occasional later temporary increase), others increase gradually. This feature is so pronounced that we may at once classify thunder into *Group A*, the sudden crash, and *Group B*, the gradually developed crash. Figure 2 [omitted], shows that these are essential differences. The strongest vibrations in the former group show a single wave (impulse) succeeded by others that are scarcely worth mentioning; the latter group have, as a rule, a rather regular series of waves whose amplitudes show a steplike increase and then a dying out. Upon computing the mean maximum amplitude of vibration of the more accurately evaluated four peals of Group A it is found to be 0.43 erg/cm² and that of the four in Group B is 0.14 erg/cm² sec. Considering the known fact that the thunder in the vicinity of the flash always sets in with the heaviest crash so that the observed interval between the first noise and the heaviest crash must develop during the propagation of the sound, one must conclude that the main vibration becomes separated from the beginning of the thunder after a considerable path has been traversed. One can also cite ear observations in this connection. Thus it appears that the thunders of Group A are generally to be considered the original, earlier vibrations; after traveling some distance they would transform themselves into those of Group B.

11. *Similarity with explosion waves.*—It follows from the preceding that any conclusions regarding the origin of thunder will be based, by preference, on the facts relating to Group A. A more detailed comparison of these records leads to the first and most surprising result that the strongest deflection always indicates a rarefaction. It is preceded by only a very brief jog that might indicate a compression. The empirical calibration, as well as a little reflection, indicates that in the apparatus the magnification of vibrations close to the period proper to the system is considerably greater than that of other vibrations, and that in the case of vibrations of brief duration the magnification is quite small. It is, therefore, not altogether out of the question that the amount of the actual condensation represented by the first small jog should exceed the rarefaction of the succeeding vibration.

It is certain that none of the following deflections even approximates in intensity that of the maximum; perhaps then the latter with its antecedent compression is to be regarded as a kind of isolated wave (Einzelwelle). This wave always introduces the vibrations in much the same manner, and is followed by the irregular deflections.

Experiments had already revealed a kind of condensation wave that bears much the same characteristics, viz, the percussion or explosion wave. When a compression or rarefaction of the air takes place with extraordinarily great speed (suddenly) at one point, there arise differences in density that no longer can be called small as compared to normal pressure, even when they have traveled considerable distances. In such a case it is not permissible to disregard the usual theory of the propagation of sound; with increasing contrast in density the velocity of propagation considerably exceeds that of sound. Here the parts of the wave having the greatest pressures advance more rapidly than those of lesser pressure and soon are in the van; so there arises here something approximating a discontinuity, a sudden jump in density. The instant this condition is established the front becomes a source of wave motion which, according to Tumlirz (3), who has further developed these points along the lines of the Riemann theory, travels backward as does a reflection and thus consumes some of the intensity of the percussion wave. In this way the density contrasts in the latter finally become so far reduced that it travels only with the velocity of sound and loses its special characteristics.

Experiments with release by explosions, cases where such waves may be observed and studied to special advantage,[3] showed that here the total amount of energy expended is of secondary importance, while the prime essential is the manner of release, its suddenness.

12. *Phenomena due to spark waves; explanation of thunder.*—No doubt the electric spark belongs to the quickest phenomena that we know. It generates tremendous compressions along its path, as shown, among others, by H. Mache & E. Haschek (4), who found that a pressure of 64 atmospheres was developed in a spark gap of 3 millimeters, although the pressure was simultaneously increased by the presence of subdivided electrode material. For this reason E. Mach (5) naturally found the spark a simple method for studying the phenomena in point by the aid of the Schlieren and interference methods. His presentation reveals all the above essential phenomena, the quick rise in pressure at the beginning of the wave, the following slower rarefaction, and the appearance of superposed waves after the highest pressure has passed. Wolff's experiments in explosions on a grand scale show similar features (6).

Let us now imagine the tiny spark magnified to the tremendous dimensions of a lightning flash, all the sequential phenomena will also show a very considerable magnification. The extraordinarily great electric repulsion between the similarly charged particles in the lightning path seems to be the principal cause of a sudden very strong rise in pressure. Here heating seems to play but a small part, and electrostriction or deformation due to electric stress would act in the opposite direction. A percussion wave due to this sudden strong pressure rise advances from it in every direction in the form of something near a cylinder wave. Primarily the total energy of the alternations in density is united in this wave; gradually, however, waves set out backward from it. The original simple detonation, which Lummer (7) thinks is the form in which we hear an explosion wave, grows weaker while variations in density of longer duration follow, the rumbling sets in. In the course of time the energy content of the detonation is no longer essentially differentiated from the more usual sound waves, the primary vibration no longer plays a special rôle and on occasion may become quite lost among the various disturbing influences or even previously change its form, so that it is introduced by a rarefaction. Though the isolated waves die out, there long persist all the accidentally formed regular wave series. Finally, the latter alone are essentially in existence.

Other details of the records agree with the above deduction. Short waves set in, in Group A, after the first strong deflections; furthermore, instrument II yields a record here that agrees essentially with that produced by bursting paper bags. Regular series of waves occur mostly in the later portions of the thunder.

13. *Explanation of the longer duration and the repeated "beats."*—The increasing breadth of the density changes due to an explosion wave may explain the increasing duration of the thunder; but some other explanation must be sought for the repeated "beats" or "nodes" that often occur several times in succession in the same peal. One is here involuntarily led to the idea—perhaps by the longer duration of the thunder—that every point of the spark path is to be regarded as an independent source of disturbance, whence the first sounds to reach the ear are from the points nearest thereto and succeeding sounds are from increasingly distant sources. Aside from the consideration that according to this theory the lightnings nearest the point of observation would generally give the longest enduring thunder, which is contrary to our experience, the laws of physics would require that in such a case the thunder would be heard as a single simple sound, because the disturbances along the whole of the spark path are practically simultaneous and set free in the same form. A comparison with the salvo from a firing squad disregards the essential components just mentioned, and therefore leads to a quite false conclusion.

Since the idea of uniform disturbance along the whole spark path does not support the explanation of the longer duration of the thunder, then the possibility of the occurrence of a finite series of intensifications or beats is the logical result from the fact that we have to do with

[3] The sudden production of a rarefaction, such as results from the sudden collapse of an exhausted glass sphere, will produce the corresponding phenomenon with a rarefaction in place of a condensation.

neither a straight-line path nor a precisely simultaneous release at all points along it. Experiments with sparks following sharply bent paths (8) showed that the distinct wave series originated by the different sections of the spark path show but imperfect mutual fusion, and in part intersect one another even when they have become very weak. The same may be predicated of sharply-bent lightning flashes, which after all are seen not to be so very frequent if one makes proper allowance for the deceptive appearances due to perspective shifting. The second set of circumstances also tends to produce these more or less independent centers of disturbance separated by longer intervals, since experiments here also have shown that the same spark produces quite different effects according to the different conditions and resistances encountered along its path. Thus points that have already been traversed by the predischarge (preliminary) offer better conductivity than others.

Probably the most important rôle is that of the currents of the atmosphere. There is no essential difference between their deflective and other effects upon explosion waves and ordinary sound waves. The greater the distance between the source and the observer, the more diverse are the paths to the observer traveled by the different parts of the wave, the longer does the thunder seem to endure, and the larger the number of "beats" (Schläge) it shows. These experiences are in agreement with the results J. N. Dorr (9) has obtained from the study of the effects of the great explosion in the quarries at Wiener-Neustadt. He found that as it traveled the original simple detonation broke up into a series of separate sounds that were in part of a different character, viz, rumblings.

14. *Relationship to the intermittent character of the lightning discharge.*—B. Walter was the first to accurately analyze the phenomenon of multiple successive partial discharges along the same lightning path, but I would not explain the multiple beats of thunder by this phenomenon. It is true that they succeed one another very rapidly at intervals which at first are the same as those of the shorter intervals revealed by instrument II. Perhaps this does enable them to have some influence upon the sound phenomenon, for it is readily conceivable that their somewhat pronounced periodicity is of mechanical origin. Thus, supposing all the air particles are hurled apart by the first partial discharge, then in the next instant they will swing back to their positions in the spark path thereby generating a condensation that of course causes a new rarefaction which greatly assists the further discharge through the same channel, of the electricity that had accumulated in the interim. This process may be repeated until the supply of electricity becomes too small. Now every time this occurs compression waves are sent out and all in all these may well produce upon the observer the impression of a more or less regular series. In counting up the time intervals of the partial discharges recorded in Walter's unfortunately very small number of photographs, I found 5 cases which would correspond to 15–40 vibrations per second, 4 cases between 40 and 65, 2 cases between 65 and 90, and 1 case of 90–115 vibrations. This distribution reminds one so strongly of that in the sound waves from the thunder revealed by instrument II (see Table 1) that one is inclined to see here a fundamental relationship. It is simply necessary to imagine that at least one portion of the waves separating from the discontinuity, originated simultaneously at the beginning and even favored the discharges that threw off the others. E. Mach has shown that explosion waves may carry others superimposed upon them.

SUMMARY.

The records made by appropriately designed recording instruments (§§1–5) show that thunder presents frequent alternations of pressure vibrations of very various durations; but these are so irregular (§6) that one can not here speak of tones, although the time interval separating two vibrations is partly short enough when they come regularly to make tones of a rattling, clanging kind whose records are quite similar to those of the clanking windowpane. The evaluation of the records of three thunderpeals (§7) revealed that intervals of 1/75 to 1/120 second were somewhat more frequent and that at first longer intervals were of less frequency, until coming to those above 1/40 second (tones lower than E), there was an increased frequency that multiplied as one approached the vibrations too long to be audible.

The essential constituent of thunder, however, were the yet longer vibrations, certainly far below the limits of audibility, which were rather violent pressure variations (the highest observed duration being more than one-half second) that were accompanied by the "beats" or "nodes" in the thunder (§8). In one case the deflections of these pressure variations amounted to 0.017 mm. Hg., or considerably more than that due to the highest sound impulse. The determination of the total energy content of the strongest recorded thunder (§10) showed it was certainly a very insignificant fraction—less than 0.000 01 of the energy of lightning. One must therefore conclude that the latter is mostly consumed by other forms of energy, such as heat and light.

Thunderpeals whose strength justifies the assumption that they have not traveled very great distances are characterized by a single initial maximum deflection of rarefaction, in no case preceded by more than a very brief condensation (§10). Their form closely simulates that of the percussion or explosion waves radiating from very suddenly produced condensations or rarefactions (§11). Their velocity of propagation is at first much greater than that of sound, but approaches this as the intensity of the density disturbance rapidly decreases on account of the retrogressive waves sent out from the discontinuity itself.

Laboratory experiments show that such explosion waves arise at an electric spark gap, where it has been possible to demonstrate there exists an extraordinarily marked pressure rise. Their properties are thus all the more evident in thunder. Thus are to be explained (§§12, 13) the rapid decrease in intensity, the change in tone color, while the irregular air currents are responsible for the increasing duration as the point of origin of the thunder retreats and for the recurring "beats."

The isolated (ausgelösten) waves are most probably due to the intermittent discharges that occur so frequently in lightning (§14).

NOTES AND REFERENCES.

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Marbe & Seddig, *in* Annalen d. Phys., (4) 1909, **30**: 579.

(2) The magnitude of this energy when considered as energy of sound is shown by the following comparison. Webster estimates that that 10^7 trumpeters can generate a tone of 1 HP. Thus the power of a trumpeter at the distance of 1 meter is still 0.02 erg/cm²sec.; i. e., even less than 1/300 of the first wave as measured in Table 2. If, therefore, it were desired to equal the total energy-content of the thunder by means of trumpeting we would need 2×10^8 trumpeters blowing in a uniformly sustained manner for 13 seconds.

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(7) **Lummer.** Ueber die Theorie des Knalles. Schlesischen Gesells. f. vaterl. Kultur, II. Abt., 1905, **83**. Jhrb., p. 2.
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(10) **Walter, B.** *in* Phys. Ztschr., 1902, **3**:168; *also* Hamburger wissens. Anstalten, Jhrb. 1903, **20**.

THE PLACE OF FORESTRY AMONG NATURAL SCIENCES.[1]

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Forestry as a natural science deals with the forest as a community in which the individual trees influence one another and also influence the character and life of the community itself. As a community the forest has individual character and form. It has a definite life history; it grows, develops, matures, and propagates itself. Its form, development, and final total product may be modified by external influences. By abuse it may be greatly injured, and the forest as a living entity may even be destroyed. It responds equally to care, and may be so molded by skillful treatment as to produce a high quality of product and in greater amount and in a shorter time than if left to nature. The life history of this forest community varies according to the species composing it, the density of the stand, the manner in which the trees of different ages are grouped, the climatic and soil factors which affect the vigor and growth of the individual trees. The simplest form of a forest community is that composed of trees of one species and all of the same age. When several species and trees of different ages occupy the same ground, the form is more complex, the crowns overlapping and the roots occupying different layers of the soil. Thus, for instance, when the ground is occupied with a mixed stand of Douglas fir and hemlock, the former requiring more light occupies the upper story, and because of its deeper root system extends to the lower-lying strata of the soil. The hemlock, on the other hand, which is capable of growing under shade, occupies the under story, and having shallow roots utilizes largely the top soil. * * *

In a forest there is altogether a different climate, a different soil, and a different ground cover than outside of it. A forest cover does not allow all the precipitation that falls over it to reach the ground. Part of the precipitation remains on the crowns and is later evaporated back into the air. Another part, through openings in the cover, reaches the ground, while a third part runs down along the trunks to the base of the trees. Many and exact measurements have demonstrated that a forest cover intercepts from 15 to 80 per cent of precipitation, according to the species of trees, density of the stand, age of the forest, and other factors. Thus pine forests of the North intercept only about 20 per cent, spruce about 40 per cent, and fir nearly 60 per cent of the total precipitation that falls in the open. The amount that runs off along the trunks in some species is very small—less than 1 per cent. In others—for instance, beech—it is 5 per cent. Thus if a certain locality receives 50 inches of rain, the ground under the forest will receive only 40, 30, or 20 inches. Thus 10, 20, and 30 inches will be withdrawn from the total circulation of moisture over the area occupied by the forest. The forest cover, besides preventing all of the precipitation from reaching the ground, similarly keeps out light, heat, and wind. Under a forest cover, therefore, there is altogether a different heat and light climate and a different relative humidity than in the open. * * *

The effect which trees in a stand have upon each other is not confined merely to changes in their external form and growth; it extends also to their internal structure. The specific gravity of the wood, its composition, and the anatomical structure which determines its specific gravity differ in the same species and on the same soil and in the same climate, according to the position which the tree occupies in the stand. Thus in a 100-year-old stand of spruce and fir the specific gravity of wood is greatest in trees of the third crown class (intermediate trees). The ratio of the thick wall portion of the annual ring to the thin wall of the spring wood is also different in trees of different crown classes. The difference in the size of the tracheids, in trees of different crown classes, may be so great that in one tracheid of a dominant tree there may be placed three tracheid cells of a suppressed tree. The amount of lignin per unit of weight is greater in dominant trees than in suppressed trees. * * *

Forestry, unlike horticulture or agriculture, deals with wild plants scarcely modified by cultivation. Trees are also long-lived plants; from the origin of a forest stand to its maturity there may pass more than a century. Foresters therefore operate over long periods of time. They must also deal with vast areas; the soil under the forest is as a rule unchanged by cultivation, and most of the cultural operations applicable in arboriculture or agriculture are entirely impracticable in forestry. Forests, therefore, are largely the product of nature, the result of the free play of natural forces. Since the foresters had to deal with natural plants which grew under natural conditions, they early learned to study and use the natural forces affecting forest growth. In nature the least change in the topography, exposure, or depth of soil, etc., means a change in the composition of the forest, in its density, in the character of the ground cover, and so on. As a result of his observations the forester has developed definite laws of forest distribution. The forests in the different regions of the country have been divided into natural types with corresponding types of climate and site. These natural forest types, which, by the way, were also developed long before the modern conception of plant formations came to light, have been laid at the foundation of nearly all of the practical work in the woods. A forest type became the silvicultural unit, which has the same physical conditions of growth throughout, and therefore requires the same method of treatment. The manner of growth and the method of natural regeneration, once developed for a forest type, hold true for the same type no matter where it occurs.

After the relation between a certain natural type of forest and the climate and topography of a region has been established, the forest growth becomes the living expression of the climatic and physical factors of the locality. Similarly, with a given type of climate and locality it is possible for the forester to conceive the type of forest which would grow there naturally. The forester, therefore, may speak of the climate of the beech forest, of the Engelmann spruce forest, of the yellow-pine forest. Thus, if in China, which may lack weather observations, we find a beech forest similar to one found

[1] Reprinted from Journal, Wash. Acad. Sci., Jan. 19, 1915, 5:41-56.